9

INTER-ELECTRODE CAPACITANCES OF TRIODE VALVES AND THEIR DEPENDENCE ON THE OPERATING CONDITION

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ABSTRACT. A double-beat method was adopted for the measurement of inter-electrode capacitances and their variations under the usual operating conditions. The theory of the method and the procedure are fully described and the experimental results obtained with eight different triodes are given in the paper. No grid-bias was employed and the effect of varying the filament current and the anode current for three different anode voltages on the inter-electrode capacitances was studied. The filament and anode-voltage applied were suited to the individual valves employed in the investigation. The main features of the experimental results are discussed and their interpretations given.

INTRODUCTION

It is now common knowledge that the effects of inter-electrode capacitances are of considerable importance, especially in the region of very high radio frequencies. In modern valves these capacitances are made as small as possible and in cases where these capacitances are not negligible methods are adopted to neutralise the effects of these inter-electrode capacitances as far as practicable. In view of the importance of the effect of inter-electrode capacitances, their actual measurements for various thermionic valves are also of considerable practical value. Since there are large and perceptible variations of the inter-electrode capacitance with the changes in the space-charge between the electrodes or with the alterations in density of the moving electrons under various operating conditions, an exact and accurate knowledge of such variations is of practical importance.

In a triode the capacitances between the three electrodes may be represented by C_{gf}, C_{ag}, and C_{af}. These are respectively the grid-filament the anode 1-grid and the anode-filament capacitances. It is obvious that when considering any one of these inter-electrode capacitances, the effect of the other two in series, joined with it in parallel can not be neglected. It is possible, however, to obtain the individual values of the inter-electrode capacitances with much difficulty, when there is no filament current and no grid or plate voltage. Many practical difficulties, however, arise when the filament carries a current and there is an anode current with a voltage on the plate or the grid. It was therefore thought desirable to develop a method of measuring the inter-electrode capacitances of a triode valve over a certain range of working conditions.

Following a double-beat resonance method measurements of the individual values of the grid-filament, anode-grid and anode-filament capacita-

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nces were made at a frequency of 1 Mc/s with different anode and filament currents for specified anode voltages. Measurements were also made with the filament cold and an estimate was made of the capacitances between the active portions of the electrodes as distinct from the total capacitance which includes the effect of wirings, leads etc. In the actual circuit, the following eight triode valves of different types were studied :—

(1) Philips E 406 (N)

(2) Philips B 406

(3) Philips B 405

(4) Cossor 41 MP

(5) Mazda PP 3/250

(6) Hivac PX 230

(7) American 2A3

(8) Philips TC 03/51

In all cases no grid-bias was applied to the grid. The maximum range of anode current corresponding to any triode could not, however, be utilised, as in most cases the anode current was found to diminish considerably as soon as the R.F. electrical oscillations were induced into the inter-electrode capacitances which were connected across the tuning condenser of the resonance system. The method and the details of the experimental procedure are set forth in a subsequent section.

PREVIOUS WORK ON INTER-ELECTRODE CAPACITANCES OF A THERMIONIC VALVE

The inter-electrode capacitances of a valve are usually measured by a bridge method using A.C. of 400 or 1,000 cycles/sec., with telephone as a balance indicator. Jones (1937) in a recent work employed a high frequency bridge and carried out some systematic measurements of the individul values of the inter-electrode capacitances of several triode valves with different anode voltages, and with varying filament and anode currents within working ranges of the valves. Measurements at 1 Mc/s. revealed the following main features :—

(1) The grid-filament capacitance increased with anode current up to the point at which the grid current began to flow.

(2) The increment of grid filament capacitance corresponding to a given anode current diminished with the increase of anode voltage.

(3) The increase of grid-filament capacitance did not depend merely on mutual conductance, anode circuit conductance or anode current. It increased with filament temperature and was therefore probably affected by the initial velocity of the electrons.

(4) The grid-anode capacitance was found to diminish with the increase of the anode current and the reduction was found to be much smaller proportionately than the increase of grid-filament capacitance.

(5) Every type of valve examined showed effect of the same kind. Even the small "acorn" triodes and pentodes showed increase of grid-filament capacitance amounting to 50% of the 'cold' value.

Much work on the inter-electrode capacitances was, however, made both theoretically and experimentally, in connection with what is known as the Miller effect. The theoretical treatment of the effect of inter-electrode capacitances in a triode network was developed by many, of whom Nichols (1919), Miller (1919), Hartshorn (1927) and Colebrook (1929)' are most outstanding. The effect was theoretically shown to be equivalent to an input impedance across the grid and the filament The conclusions about the input impedance which again could be resolved into input capacitance and input resistance of the triode network and also about voltage amplification were in some measure verified by the measurements of the inter-electrode capacitances and of the voltage amplification.

THEORETICAL CONSIDERATIONS— EQUIVALENT NET WORK OF A TRIODE

A triode is represented in Fig. 1, where Z_a and Z_g are the external

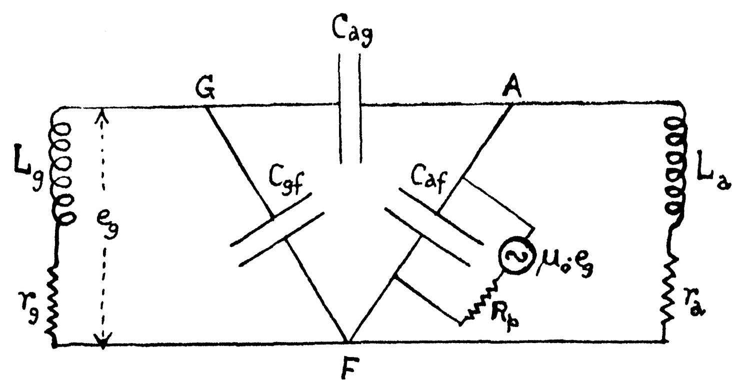


Fig. 1

Triode Net work

impedances of the anode-filament and the grid-filament circuits respectively. Let C_{gf}, C_{ag} and C_{af} be the grid filament, the anode-grid and the anode-filament capacitances respectively. Representing the resistance to the convection current between the filament and the anode by R_p, which is in shunt with the capacitance C_{af}, and remembering that a potential e_g impressed on the grid introduces an E.M.F. equal to $\mu_0 \cdot e_g$ in the anode circuit, the input impedance can be obtained by including in the anode circuit a fictious generator giving a voltage $\mu_0.e_g$ and solving the Kirchoff equations for the network. (here μ_0 is the amplification factor of the valve).

Unless the frequency is very high and is o.er 10^6 cycles per sec. the anode-filament capacitance C_{af} can be neglected, as it is shunted by R_p which is low compared with the impedance due to C_{af}. For low frequencies ($\omega<10^6$) neglecting C_{af}, the effective input impedance is given by

$$Z_g=\frac{1}{jC_{gf}\omega}\;\frac{1+j\omega C_{ag}r}{1+j\omega C_{ag}r+\dfrac{C_{ag}}{C_{af}}\,(1+\mu_0 r'/R_p)} \quad \ldots \quad (1)$$

where $r=\dfrac{R_p\ Z_a}{R_p+Z_a}$ and $\omega=2\pi\times$ frequency.

Writing the general form for Z_a, *viz.*, $Z_a=r_a+jx_a$

it can be shown that $Z_g=-\dfrac{ac+bd}{c^2+d^2}+j\dfrac{ad-bc}{c^2+d^2}$ ... (2)

$$=-r_g+jx_g$$

where the coefficients have the values

$$a=R_p+r_a-\omega R_p r_a C_{ag}$$

$$b=\omega R_p r_a C_{ag}+x_a$$

$$c=\omega^2 R_p r_a C_{gf} C_{ag}+\omega x_a(C_{gf}+C_{ag}+\mu_0 C_{ag})$$

$$d=\omega^2 R_p x_a C_{gf} C_{ag}-\omega R_p(C_{gf}+C_{ag})-\omega r_a(C_{gf}+C_{ag}+\mu_0 C_{ag})$$

Assuming again the output impedance to be *inductive, i.e.*, putting $x_a=\omega L_a$ and denoting the amplification factor of the valve by μ_0, the input resistance r_g and input capacity C_g are given by

$$r_g=\frac{R_p C_{ag}(R_p r_a C_{ag}+r_a^2\mu_0 C_{ag}+r_a^2 C_{ag}-\mu_0 L_a)}{[R_p(C_{gf}+C_{ag})+r_a(C_{gf}+C_{ag}+\mu_0 C_{ag})]^2} \quad \ldots \quad (3)$$

and

$$C_g=C_{gf}+C_{ag}\left(1+\frac{\mu_0 r_a}{R_p+r_a}\right) \quad \ldots \quad (4)$$

When $r_a=0$ the input capacity is reduced to

$$C_g=C_{gf}+C_{ag} \quad \ldots \quad (5)$$

For high frequencies ($\omega>10^6$) where the anode-filament-capacitance C_{af} cannot be neglected, the effective input impedance will be given by

$$Z_g=\frac{ac+bd}{c^2+d^2}+j\frac{bc-ad}{c^2+d^2}$$

where the coefficients have the values

$$a=\omega R_p r_a(C_{af}+C_{ag})+x_a$$

$$b=\omega R_p x_a(C_{af}+C_{ag})-R_p-R_a$$

$$c=\omega r_a(C_{gf}+C_{ag}+\mu_0 C_{ag})+\omega R_p(C_{gf}+C_{ag})-\omega^2 R_p r_a(C_{gf}C_{ag}+C_{gf}C_{af}+C_{ag}C_{af})$$

$$d=\omega x_a(C_{gf}+C_{af}+\mu_0 C_{af})+\omega^2 R_p r_a(C_{gf}C_{ag}+C_{gf}C_{af}+C_{ag}C_{af})$$

Since ω is large, we can neglect the ω terms of the lower order in comparison with those of the succeeding and higher orders.

Now putting $x_a=\omega L_0$ or $\frac{1}{\omega C_0}$, we get approximately

$$r_g = 0$$

$$C_g = \frac{C_{gf}C_{af}+C_{gf}C_{ag}+C_{ag}C_{af}}{C_{ag}+C_{af}}$$

$$= C_{gf} + \frac{C_{ag}C_{af}}{C_{ag}+C_{af}} \qquad \dots \quad (6)$$

Thus at very high frequencies the input capacity of a triode network is practically Independent of the constants of the external output circuit. It can be looked upon as a 'grouped' capacitance with the grid-filament capacitance placed in parallel with series combination of the anode-grid and the anode-filament capacitances. The input capacity can therefore vary only when the individual capacitances change with the change of the working conditions.

METHOD OF DETERMINING THE INDIVIDUAL VALUES OF INTER-ELECTRODE CAPACTIANCES

(a) Individual values of capacitances with no filament current and no anode voltage

The method adopted consists in taking three separate observations of grouped capactiances :

(i) With grid and filament connected together, the capacitance across the anode and grid (or filament) is determined.

Denoting this by C_1, we have

$$C_1 = C_{ag} + C_{af} \quad \text{(grid and filament shorted)} \qquad \dots \quad (7)$$

(ii) With anode and filament connected together, the capacitance across the grid and anode (or filament) is next determined.

Denoting this by C_2, we have

$$C_2 = C_{ag} + C_{gf} \quad \text{(anode and filament shorted)} \qquad \dots \quad (8)$$

(iii) With anode and grid connected together, the capacitance across the filament and grid (or anode) is then found.

If this is C_3, we have

$$C_3 = C_{gf} + C_{af} \qquad \text{(anode and grid shorted)} \qquad \dots \quad (9)$$

From (7), (8) and (9) it is evident

$$\left.\begin{aligned} \tfrac{1}{2}(C_1+C_2-C_3) &= C_{ag} \\ \tfrac{1}{2}(C_1+C_3-C_2) &= C_{af} \\ \tfrac{1}{2}(C_2+C_3-C_1) &= C_{gf} \end{aligned}\right\} \qquad \dots \quad (10)$$

By measuring C_1, C_2 and C_3 the individual values of C_{ag}, C_{gf} and C_{af} are then obtained from (10).

(b) Individual values of inter-electrode capacitances of the triode under working conditions with filament and anode voltages

From the theoretical considerations it is evident that in the triode network with an output circuit employed under the working conditions, the input capacity of the triode at very high radio frequencies is approximately given by (6), viz.,

$$C_g = C_{gf} + \frac{C_{ag}C_{af}}{C_{ag} + C_{af}}$$

Thus, (i) if a comparatively large capacity ($C \gg C_{af}$) is placed across the anode-filament capacitance, the input capacity as given by (6) will be reduced to

$$C_1 = C_{gf} + C_{ag} \qquad (11)$$

Again, (ii) if a comparatively large capacity ($C \gg C_{ag}$) is inserted across the anode-grid capacitance, the input capacity as given by (6) under such condition will be given by

$$C_2 = C_{gf} + C_{af} \qquad \ldots \quad (12)$$

Next, (iii) when a relatively large capacity ($C \gg C_{gf}$) is placed in parallel with the grid-filament capacitance, the effective capacity between the anode and the grid will be given by

$$C_3 = C_{ag} + \frac{C_{gf}C_{af}}{C_{gf} + C_{af}} = C_{ag} + C_{af} \qquad \ldots \quad (13)$$

from (11), (12) and (13), the individual values of the inter-electrode capacitances of the triode come out as follows :

$$\left.\begin{aligned} C_{gf} &= \frac{C_1 + C_2 - C_3}{2} \\ C_{af} &= \frac{C_2 + C_3 - C_1}{2} \\ C_{ag} &= \frac{C_3 + C_1 - C_2}{2} \end{aligned}\right\} \qquad \ldots \quad (14)$$

For measuring the variations of the individual capacitances for various values of filament current and anode current and under specified values of the anode voltage, the values of the 'grouped' capacitances C_1, C_2 and C_3 are measured for different values of filament current and anode current under the desired conditions. Curves are then drawn showing the variations of C_1, C_2 and C_3. From these curves, the variations of the individual inter-electrode capacitances for varying values of filament current and anode current under desired conditions are obtained with the help of (14).

METHOD OF MEASURING THE 'GROUPED' CAPACITANCES AND EXPERIMENTAL PROCEDURE

The experimental arrangement is shown in Fig. 2 and the procedure is described below :

The particular 'grouped' capacitance C_1, C_2 or C_3 was connected by extremely short leads in parallel with the tuning condenser of capacity C of

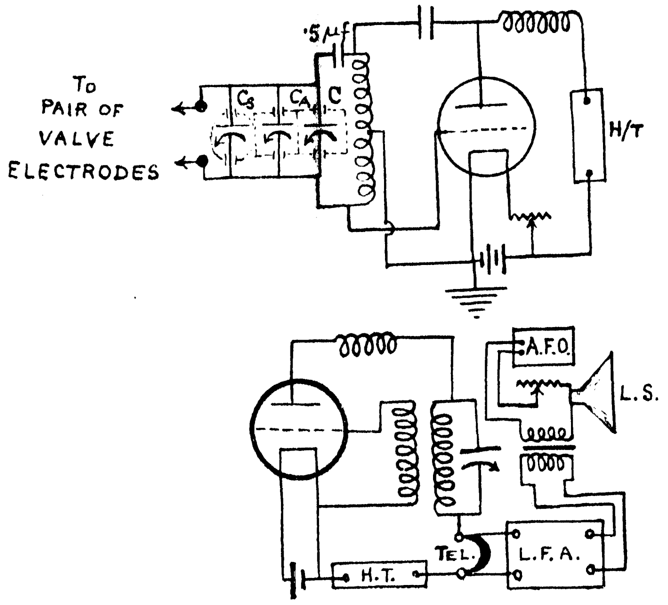


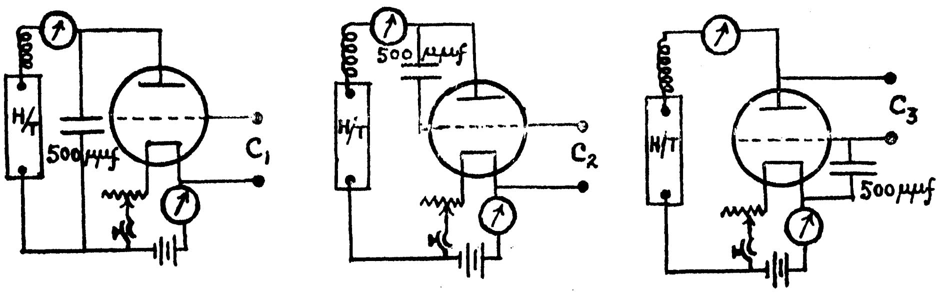
FIG. 2

Experimental arrangement

A. F, O—Audio frequency oscillator
L. F. A.—Low frequency amplifier
L. S.—Loud speaker
Tel.—Telephone

the oscillatory circuit of a suitable Hartley oscillator. The change in the value of this 'grouped' capacitance, when the inter-electrode space was filled with electrons, was balanced by changing the capacity of a small calibrated variable air condenser C_A in parallel with C and the desired 'grouped' capacitance so that the total capacity $(C_{1,2,3}+C+C_A)$ remained constant. High frequency oscillations from the oscillator were received by an oscillator-detector valve-circuit. When the detector circuit was nearly in tune with the oscillator, the familiar heterodyne whistle was heard in the telephone placed in the anode-circuit of the receiver. The audio-frequency voltage developed across the telephone was amplified by a three-valve amplifier of the conventional type and fed into a loudspeaker which gave a loud musical note. On introducing into the same loudspeaker an audio-frequency current from an audio-oscillator capable of producing an intense note of fixed frequency, beats were heard by suitably adjusting the heterodyne frequency. The latter adjustement was made by varying the small variable condenser C_A. In parallel with C_a was also used a specially constructed variable vernier condenser C_s construcetd from a spherometer. With this condenser very small variations of capacity could be effected. A variable resistance was placed in the secondary of the transformer used with the loudspeaker to match the intesity of the heterodyne whistle with that of the audio-frequency note. Adjustments of the small variable condenser C_A or the spherometer condenser C_s in the oscillator to produce no beats were then successively made with filament 'cold' and with different values of the filament current and anode current which were noted. The variation in the value of any particular 'grouped' capacitance with the change in the filament current (or the anode current) was thus accurately determined over a certain range of filament current or anode current suited to the value under examination.

A suitable D.C. meter with a coil of H.F. impedance was inserted in the anode circuit for measuring the anode current and a suitable ammeter in the filament curcuit for measuring the filament current of the experimental valve.



(a) (b) (c)

FIG. 3

Experimental valve connection

In Fig. 3 are shown the electrical connections and the insertion of a condenser of relatively large capacity in the circuit of the experimental valve for obtaining the 'grouped' capacitances C_1, C_2 and C_3.

In the spherometer condenser a circular disc formed the fixed plate of this air-condenser and a similar circular disc, placed vertically above and parallel to the former, could be pushed by the central leg (which was cut short) when the graduated spherometer disc was given a right-handed turn. On giving a left-handed turn to the spherometer disc, the central leg would move up and the upper circular disc of the vernier condenser could be pulled up by a steel spring suitably fixed. Earthed guard-rings made up of thin brass foils, were inserted round the two parallel discs. The spherometer disc had a graduated scale with 50 big divisions, each of which was further divided into 5 small divisions so that a turn through one small division would mean a very small change of capacity of the order of $10^{-3}\mu\mu f$.

It can be seen from the circuit diagram of the oscillator system that one plate of each of the condensers which were in parallel was also earthed. It was so arranged that the rotating plates of the condensers each of which was enclosed inside a shielded box were at the earthed end. Each of the smaller condensers was varied by turning a long glass rod fixed to the condenser knob. The effect of hand capacity was thus reduced to a minimum.

EXPERIMENTAL RESULTS

(*i*) *Measurements of inter-electrode capacitances without filament current and without anode voltage.*

Following the method outlined in Sec. 4(a) the inter-electrode capacitances with no electrons in the inter-electrode space were then determined. The results are given in Table 1. The amplification factor as obtained by C_{gf}/C_{af} is also entered in the table.

TABLE I

Capacitances in $\mu\mu F$

Valves	C_{gf}	C_{ag}	C_{af}	
1. Philips E 406 (N)	9.0	8.3	3 1	3.0
2. ,, B 406	5.6	4.8	3.8	1.4
3. ,, B 405	5.8	4.7	4.65	1.3
4. Cossor 41 MP	9.35	8.15	4.75	1.9
5. Mazda PP3/250	11.9	12 2	5.2	2.3
6. Hivac PX 230	5.7	7.9	2 75	2.7
7. American 2A3	7.4	14.4	6 8	1.1
8. Philips TC 03/5,	3.9	3.5	—	—

(*ii*) *Measurement of inter-electrode capacitances with varying anode current for three different anode voltages :*

The method outlined in sections 4(*b*) and (5) was followed :

First a capacity $500\mu\mu f$ was placed across the anode-filament electrodes. With such a relatively large capacity, the effective capacity between the grid and filament electrodes was measured. This measurement gave the value of the 'grouped' capacitance C_1, where $$C_1 = C_{gf} + C_{ag} \qquad \dots \quad (15)$$

Secondly, with a capacity 500$\mu\mu f$ across the anode-grid electrodes, the effective capacity between the grid and the filament electrodes was measured. This gave the value of the 'grouped' capacitance C_2, where

$$C_2 = C_{gf} + C_{af} \qquad \dots \quad (16)$$

Philips B406

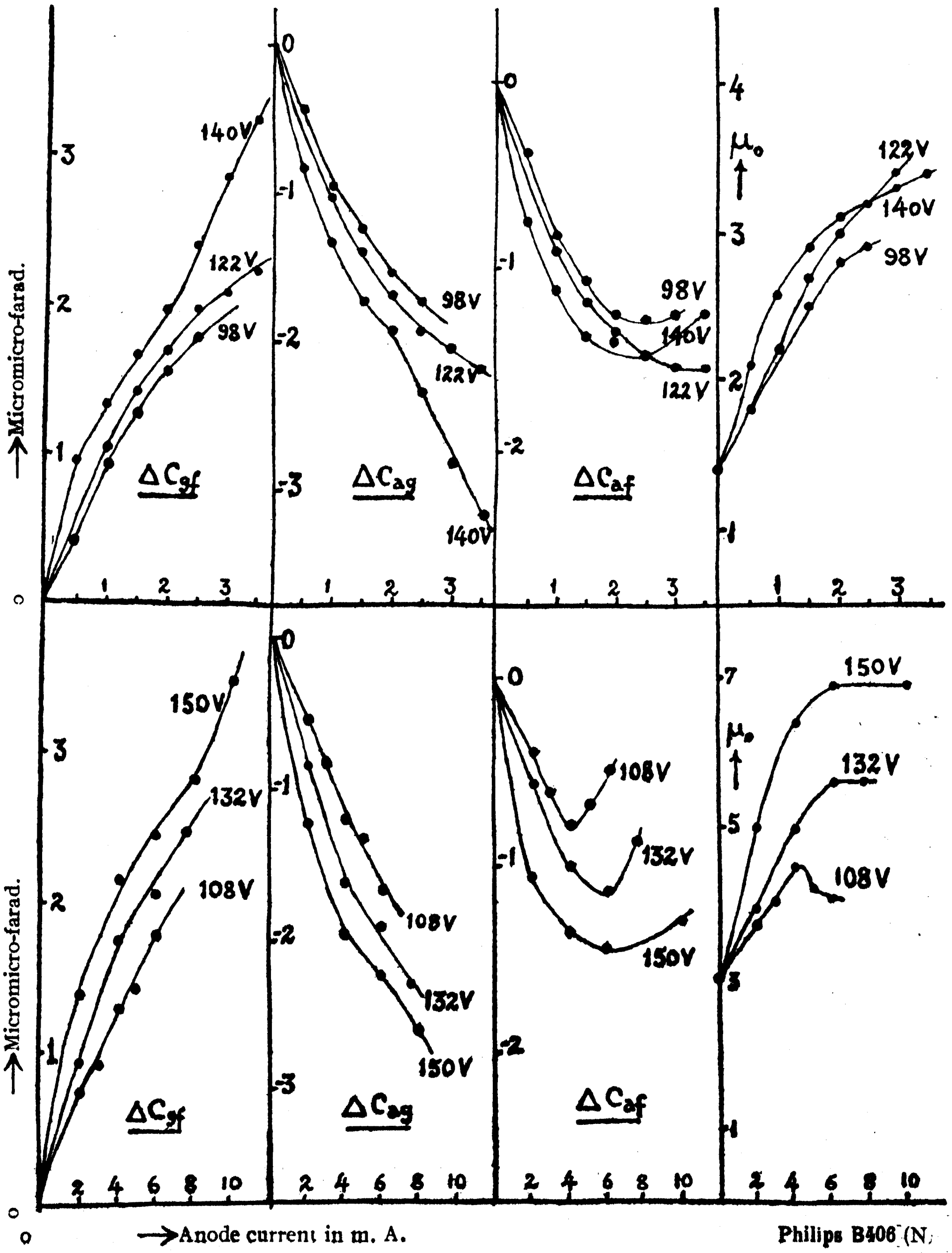


FIG. 4

Thirdly, with a capacity 500 $\mu\mu f$ placed in parallel with the grid-filament capacitance, the effective capacity between the anode and the grid electrodes was measured. This yielded the value of the 'grouped' capacitance C_3,

where $$C_3 = C_{ag} + C_{af} \quad \dots \ (17)$$

Cossor 41MP

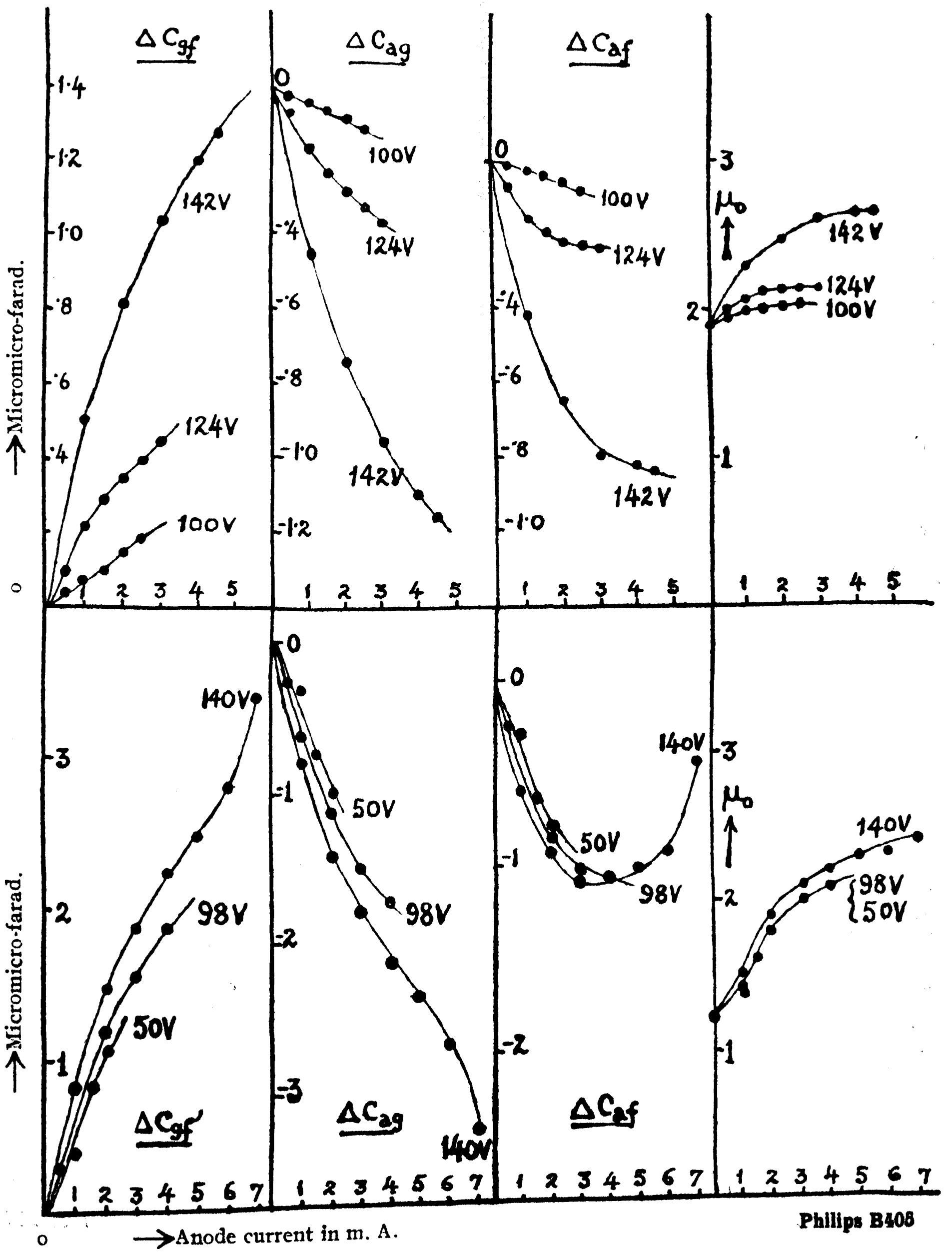


FIG. 5

The values of C_1, C_2 and C_3 were measured for no filament current (*i.e.*, for no anode current). With increasing values of filament current and anode current for a fixed anode voltage, the changes of C_1, C_2 and C_3 were then obtained and curves were drawn showing ΔC_1, ΔC_2 and ΔC_3 against

American $2A_3$

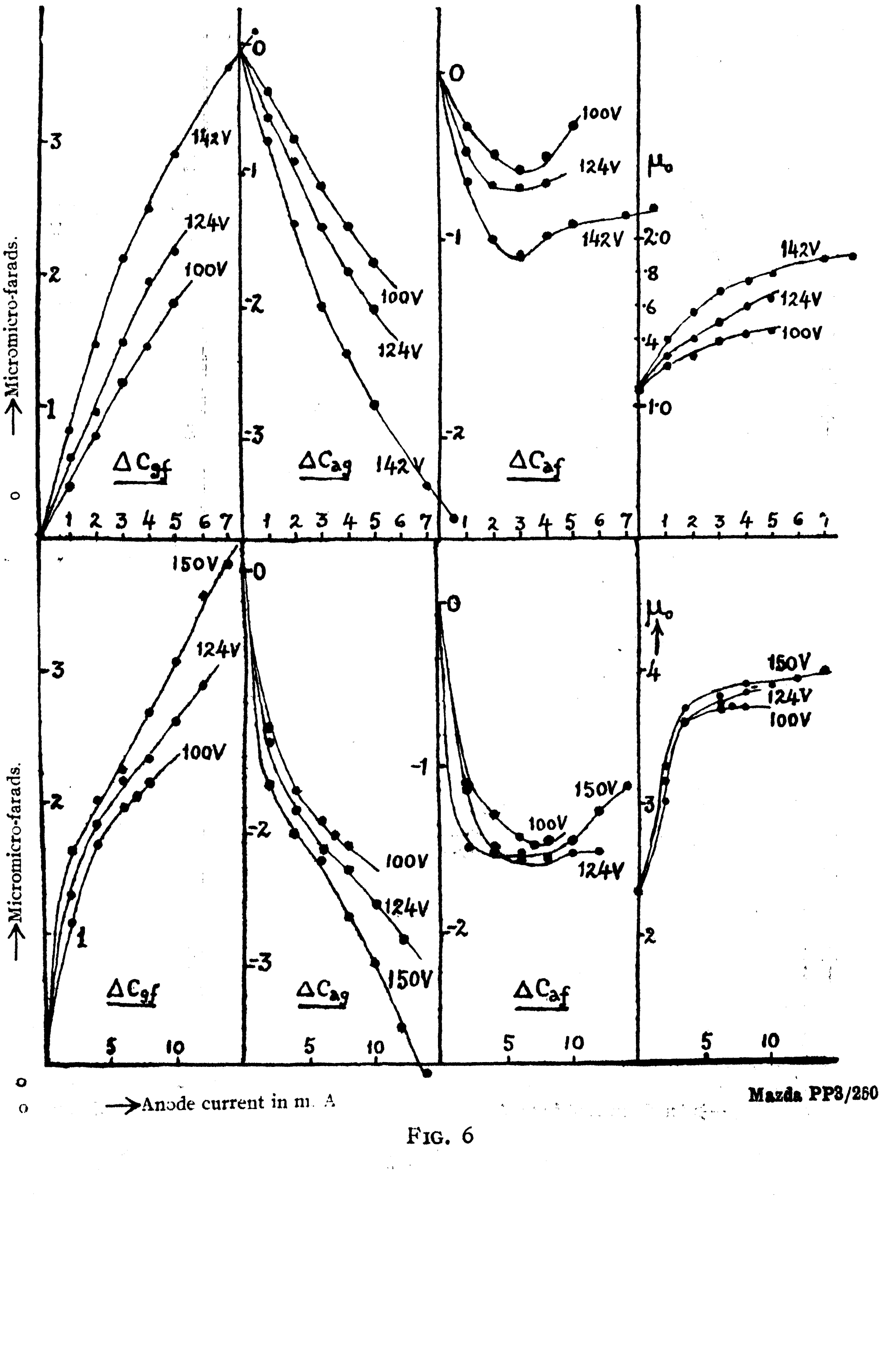


Fig. 6

anode current for three different anode voltages. From these curves the changes in the individual inter-electrode capacitances *viz.*

ΔC_{gf}, ΔC_{ag} and ΔC_{af} were determined from (14) for different values of the anode current and for the three fixed anode voltages. Since the inter-electrode capacitances for no filament current were originally measured the acutal values of C_{gf}, C_{ag} and C_{af} could be easily found for different anode-currents for the three fixed anode voltages.

The changes in the individual capacitances *i.e.* ΔC_{gf}, ΔC_{ag} and ΔC_{af} for the Philips E406 (N) and B406 valves are shown Fig. 4. In Figs. 5 and 6 are given the variations of the inter-electrode capacitances for the Philips B405, Cossor 41MP, Mazda PP3/250 and American 2A3 valves. Similar variations for the Hivac PX230 and the Philips TC 03/51 are illustrated in Fig. 7, the values of μ_0 as obtained from C_{gf}/C_{af} are also shown in Figs. 4, 5 and 6. Variations of the inter-eiectorode capacitances with anode current for three fixed anode voltages were studied.

SUMMARY OF EXPERIMENTAL RESULTS

Summing up all the experimental results with triodes having no grid-bias, the main features which were observed, except in the case of the Philips TC 03/51 valve, are the following :—

I. (*a*) There was a steady increase of the grid-filament capacitance with the incrase of anode current within the experimental range.

(*b*) For the same anode current the observed of the grid-filament capacitance was larger for a larger anode voltage, except in the case of Hivac PX 230 valve, where the increase was smaller for a larger anode voltage.

II. (*a*) There was a comparatively slow but steady decrease of the anode-grid capacitance with the gradual increase of anode current.

(*b*) For the same anode current, the observed decrease of the anode-grid capacitance was large for a larger anode voltage, except in the case of Hivac PX 230 valve, where the decrease was smaller for a larger anode voltage.

III. There was a gradual decrease of anode-filament capacitance with the anode current with an occasional increase with further increase of anode current.

IV. There was a rapid rise in the amplification factor as obtained from the ratio of C_{gf}/C_{af} with anode current assuming or tending to assume a saturation value for higher values of the anode current.

The ultra-short wave transmitting valve (Philips TC 03/51) showed the following distinctive features :—

(*a*) The grid-filament capacitance was found in general to decrease steadily with the increase of the anode current up to a point beyond which there was a rise again with further increase of anode current. The turning point appeared at a higher value of the anode current for the higher anode voltage ; *e.g.*, the value of ΔC_{gf} was found to increase at 10 m.A., 5 m.A. and

2 m.A. respectively for 150 volts, 120 volts and 90 volts on the anode (see FIG. 7).

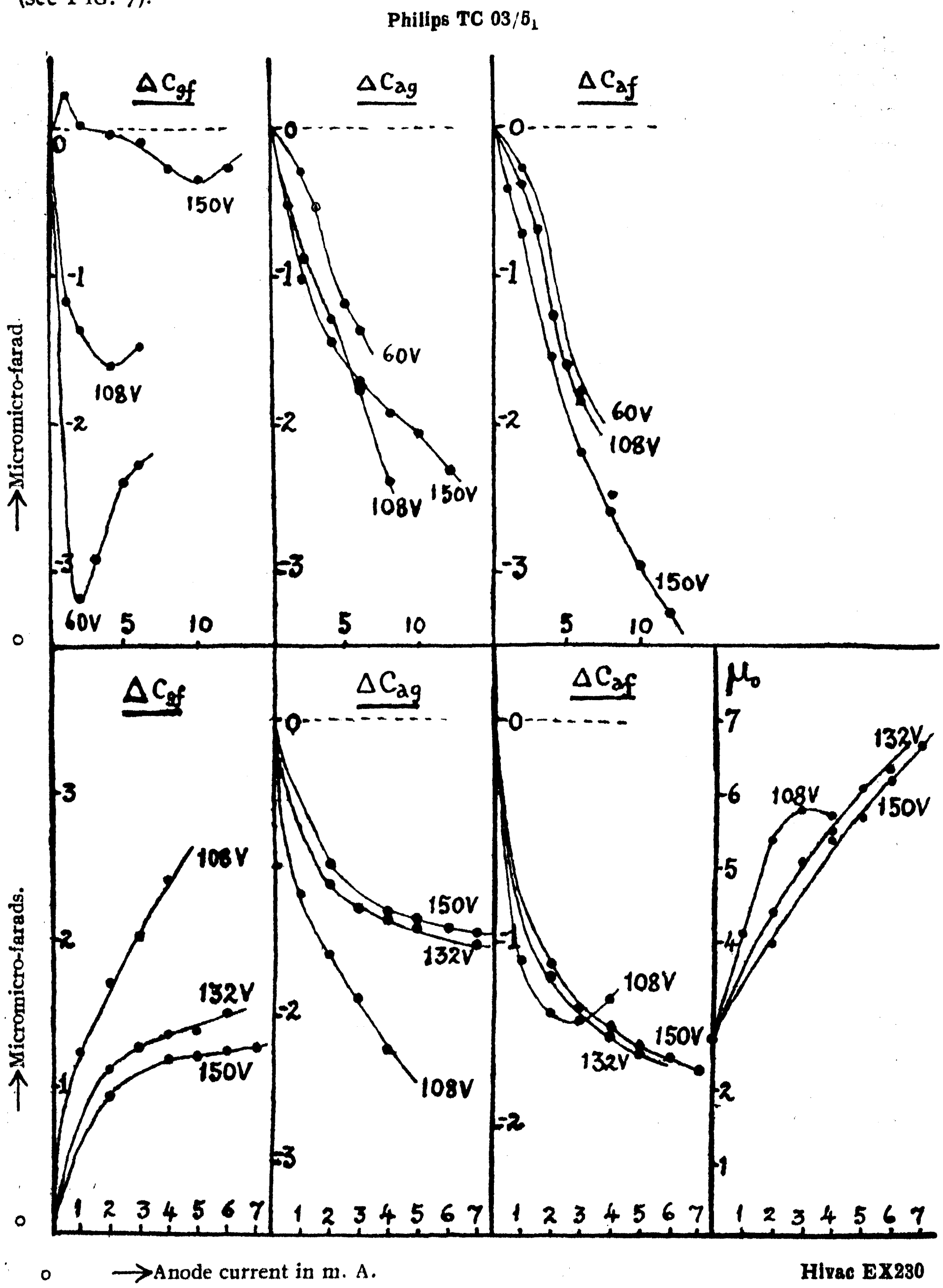


FIG. 7

(*b*) For 150 volts on the anode there was an initial increase of the grid-filament capacitance, a feature which was not observed for the lower anode voltages.

(*c*) The anode-grid and the anode-filament capacitances were found to decrease steadily with the increase of the anode voltages for all the three anode voltages employed.

The observed variations of the grid-filament capacitance and of the anode-grid capacitance for the *maximum* change of anode current for different anode voltages are shown in TABLE II for all the thermionic valves :—

TABLE II

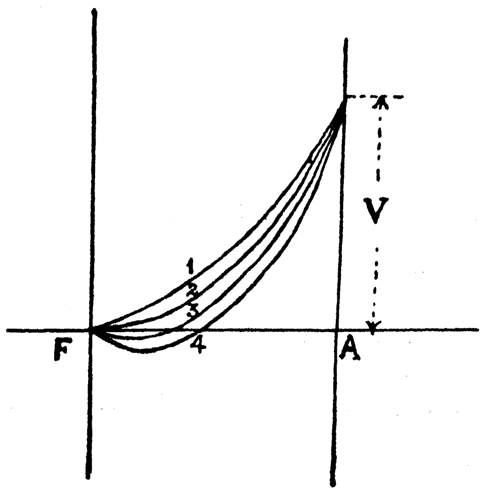
Valves	V_a Volts	Δi_a (m.A.)	ΔC_{gf} ($\mu\mu$F)	ΔC_{ag} ($\mu\mu$F)
(1) Philips E406 (N)	150	0-10	+3.46	−3.19
$C_{gf}=9.0\mu\mu$F	132	0-7.5	+2.48	−2.30
$C_{ag}=8.3$,,	108	0-6	+1.77	−1.66
(2) Philips B 406	140	0-3.5	+3.25	−3.16
$C_{gf}=5.6\mu\mu$F	122	0-3.5	+2.23	−2.17
$C_{ag}=4.8$,,	98	0-2.5	+1.78	−1.27
(3) Philips B 405	140	0-7	+3.40	−3.25
$C_{gf}=5.8\mu\mu$F	98	0-4	+1.86	−1.74
$C_{ag}=4.7$,,	50	0-2	+1.06	−0.96
(4) Cossor 41MP	142	0−4.5	+1.27	−1.16
$C_{gf}=9.35\mu\mu$F	124	0−3	+0.44	−0.37
$C_{ag}=8.15$,,	100	0−2.5	+0.19	−0.12
(5) Mazda PP 3/250	150	0−14	+3.80	−3.83
$C_{gf}=11.9\ \mu\mu$F	132	0−12	+2.89	−2.80
$C_{ag}=12.2$,,	108	0−8	+2.15	−2.1
(6) Hivac PX 230	150	0−7	+1.27	−1.44
$C_{gf}=5.7\mu\mu$F	132	0−6	+1.51	−1.53
$C_{ag}=7.9$,,	108	0−4	+2.41	−2.25
(7) American 2A3	142	0−8	+3.82	−3.61
$C_{gf}=7.4\mu\mu$F	124	0−5	+2.16	−2.03
$C_{ag}=14.4$,,	100	0−5	+1.78	−1.68
(8) Philips TC/03/5I	150	0−12	−0.26	−2.32
$C_{gf}=3.9\mu\mu$F	108	0−8	−1.56	−2.39
$C_{ag}=3.5$,,	60	0−6	−2.28	−1.36

INTERPRETATION OF EXPERIMENTAL RESULTS

We shall now explain the experimental results regarding the variations of the grid-filament and the anode-grid capacitances with the variations of the anode current. The nature of the variations of the anode-filament capacitance (or of the ratio C_{gf}/C_{af}) would, however, depend on the rates of change of the grid-filament and the anode-grid capacitances with anode current for the individual valves.

Any inter-electrode capacitance of a triode should naturally depend on the presence of electrons coming from the hot filament towards the anode. The electrons usually bring about two effects: (1) a reduction in the dielectric constant of the inter-electrode medium and (2) a conductivity effect across the electrodes. The first would cause a steady reduction of the inter-electrode capacitance with the increase of the electronic current through it. The second would involve a slight and apparent increase of the inter-electrode capacitance, since the conductivity acquired by the medium introduces a damping (a series resistance) in the resonance circuit, thus increasing the apparent capacitance between the two electrodes in the conducting medium, the other factors, namely the inductance and resistance of the LCR-circuit remaining the same for a given frequency of the alternating field. Thus with a larger anode current, when there would be a greater conductivity effect, the apparent increase of the inter-electrode capacitance would also be greater. In the experiments of Khastgir and Chowdhury (1940), on dielectric constants of electronic medium, this apparent increase of the inter-electrode capacitance was found to be negligibly small for lower radio frequencies (less than 400 Kc/s) and for about 1 Mc/s, this was found to be about half the decrease of the same capacitance due to the reduction of the effective dielectric constant of the electronic medium. The conductivity effect due to high frequency oscillations in the electronic medium during observation is, however, extremely small in the high-vacuum thermionic valves. On the whole, therefore, the inter-electrode capacitance would drecease with the increase of electron concentration, *i.e.*, with the increase of anode current (for a given anode voltage). This normal feature is usually observed in the case of the *anode-grid capacitance.*

In the case of the *grid-filament capacitance* also a similar decrease of the capacitance value with the increase of anode current would be observed, *provided there is no space-charge.* In the neighbourhood of the filament, for low anode voltage and large filament current, there is always some space-charge. The effect of the space-charge is significant. Referring to Fig. 8, where some poten-



Effect of space charge.

FIG. 8

tial distribution curves between the anode and the filament for different amounts of space-charge are shown, it is clear that the effect of space-charge is to produce a curvature of the potential distribution curve. When the space-charge is sufficient, the potential curve shows a negative gradient in the neighbourhood of the filament and the curve passes through the zero potential (with respect to the filament) at some distance x from the filament (curves 3 and 4). At distances less than x, the potential shows a negative value. With increasing anode potential, the space-charge becomes small and the distance x shortens. For sufficiently high anode potential, when the space-charge is considerably reduced, the potential gradient becomes always positive (curves 1 and 2). In short it can be said that owing to the space charge and the influence of initial velocities of the electrons, the surface of zero potential shifts shightly towards the anode and the effective distance between the grid and the filament is slightly reduced as the space-charge is increased. With a large space-charge, therefore, there will be an increase in the effective capacity between the electrodes. In the grid-filament space this space-charge effect usually overcomes the normal effect (when there is no space-charge), *viz.*, a decrease in the effective capacity of the grid-filament space due to the reduction of the effective dielectric constant of the electronic medium. An increase in the effective value of the grid-filament capacitance with an increase in the anode current is thus expected from this point of view. Further, according to this view the increase of the grid-filament capacitance for a given anode current would be less for a higher value of the anode voltage.

While the former conclusion, *viz.*, an increase of the grid-filament capacitance with an increase of anode current, is substantiated in our experiments within the range under investigation, the latter conclusion, regarding the relative increase of the grid-filament capacitance with the magnitude of the anode voltage for a given anode current, is, however, found to hold only in the case of one valve (Hivac PX 230). With the remaining valves the sequence was found to be reversed. This indicates that there must be some other factor or factors affecting the variation of the inter-electrode capacitances. The main factor appears to be the emission of secondary electrons at the grid and the anode for the higher anode voltages. When such secondary emission takes place at the grid surface, the latter acquires a positive potential. With a perceptible positive potential on the grid, the following effects will have to be considered.

(*i*) In *the grid-filament space*, the electrons flowing from the filament to the grid would move faster with a positive than with a neutral grid. Hence for a given thermionic current given by $n.e.v.$ (where n=electron density, v=electron velocity and e=electronic charge), the average electron density would be less, as the velocity of the electrons would be larger, so that the decrease of the grid-filament capacitance due to change of the dielectric constant of the electronic medium would be smaller for the higher anode voltages for which there is secondary emission. Thus for higher anode voltages, the increase of the grid-filament capacitance due to space-charge would indeed appear larger. The experimental result that in all valves excepting the one already mentioned, the increase of grid-filament capacitance, for the same anode current, was greater for the higher anode voltages can thus be explained as due to the effect of secondary emission at the grid surface. In the Hivac PX 230 valve, the anode-current vs. filament-current for the higher anode voltage clearly showed that the secondary emission was indeed small, so that the exceptional result with this valve are to be expected.

The increased conductivity due to the emission of secondary electrons for higher anode voltages would, again, cause an apparent increase in the inter-electrode capacitances. This would also affect the relative increase of the grid-filament capacitance for different anode voltages in a way similar to what has been actually observed with most of the valves. (*ii*) The effect of the secondary emission will also explain the sequence observed in the decrease of the *anode-grid capacitance* of most of the valves with different amounts of anode voltages. Positive potential on the grid would retard the electrons going from the grid to the anode. As a consequence with a high anode voltage producing secondary emission, for the same anode current, the number of electrons per c.c. would be larger than when there is little or no secondary emission for the lower anode voltages. This would result in a larger decrease of the anode-grid capacitance for the higher anode voltages. The observed result that for a given anode current the decrease of anode-grid capacitance for most of the triodes under examination was larger for the higher anode voltages can thus be explained. With little or no secondary emission at the grid as in the case of Hivac PX 230 triode, the decrease of the anode-grid capacitance would evidently be smaller with higher anode voltages, as with a higher value of anode voltage the electron velocity v would be much larger, and the electron density n would be necessarily smaller for the same value of the anode current given by $n.e.v$.

It is possible that other factors may also affect the variation of the inter-electrode capacitances. The works of Schottky (1914), Epstein (1919), Fry (1920) and others on the increase of grid-filament capacity due to the space-charge effect clearly showed the dependence of grid-filament capacitance on the inter-electrode distances and the potential applied to the anode. The relative positions of the electrodes in different valves would thus, to some extent, determine the effective value of the inter-electrode capacitances.

In the case of the Philips TC 03/5$_1$ valve, the variation of the inter-electrode capacitance between the grid and the filament with the changes of anode current was found to be somewhat different from what is generally observed with the other valves (Fig. 7). The relative positions of the electrodes of the transmitting valve must have been such that the space-charge effect on the grid-filament capacitance did not immediately come into operation. With a high voltage the effect made its appearance for a relatively large value of the anode current. With a lower anode voltage the effect showed itself at a smaller value of the anode current. Beyond this value of anode current, therefore, an increase in the grid-filament capacitance was observed with further increase of the anode current. For anode currents less than this value, there was a decrease in the value of the grid-filament capacitance as expected. An initial increase in the grid-filament capacitance for the highest anode voltage employed ($V_a = 150$ volts) was, however, an unusual observation. But this can perhaps be explained as due to the copious emission of secondary electrons at the anode and the grid for such high anode voltage. The increase in the conductivity of the inter-electrode space due to the emission of secondary electrons at a high anode voltage would effect a perceptible apparent increase in the value of the inter-electrode capacitance. For smaller anode currents therefore this increase in the inter-electrode capatitance will make itself felt in the final result. For smaller anode voltages, for which there is no secondary emission, this initial increase is not expected. This is exactly what was observed.

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